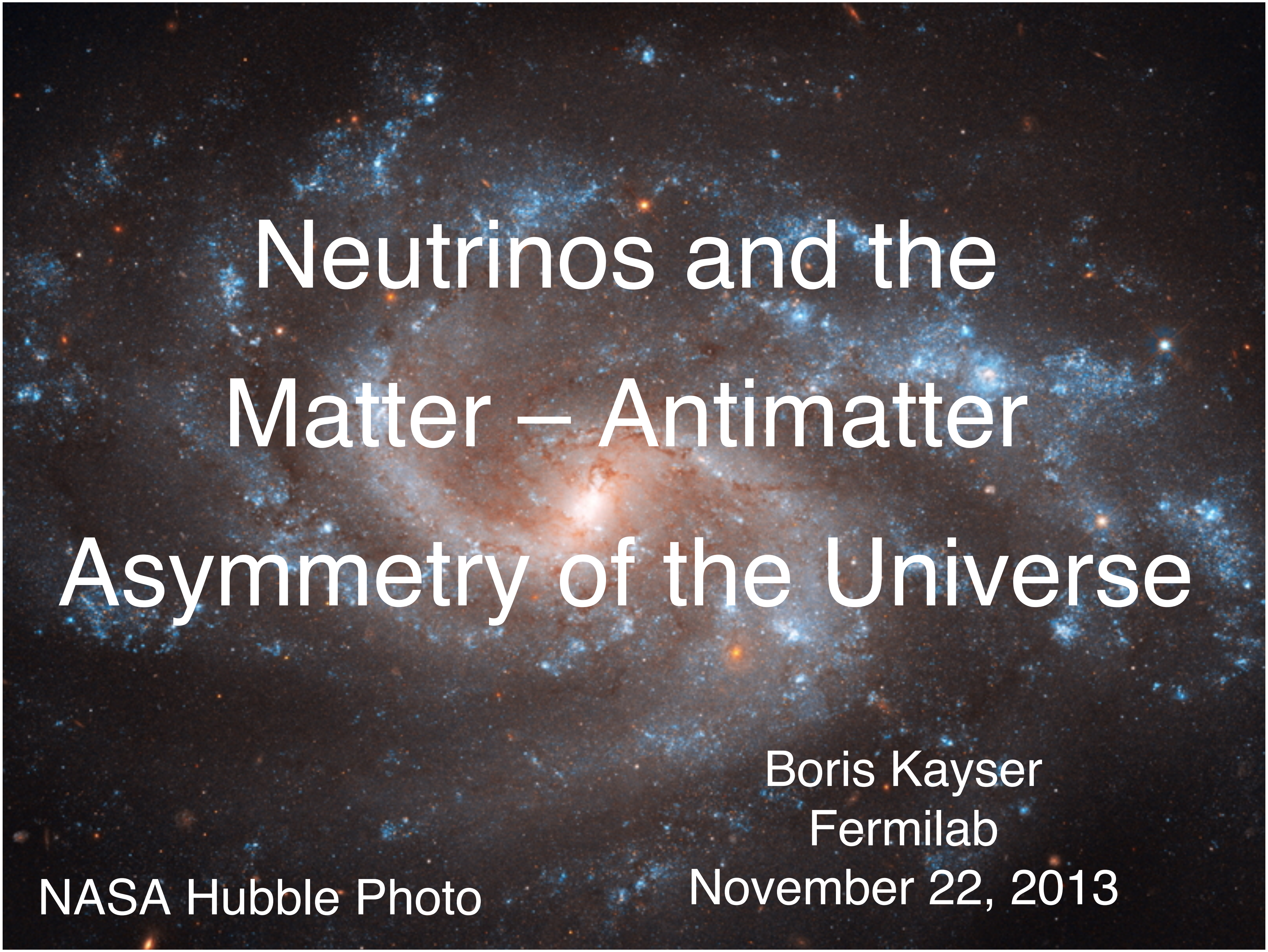


Neutrinos and the Matter – Antimatter Asymmetry of the Universe

Boris Kayser
Fermilab
November 22, 2013

NASA Hubble Photo

We are all indebted to wonderful neutrino experiments, past, present, and future.

An incomplete list —

HOMESTAKE, Kamiokande, IMB, Super-Kamiokande, SNO, GALLEX, SAGE, Borexino

MINERvA

K2K, MINOS, T2K, ICARUS, OPERA, MINOS+, NOvA, LBNE, DAEdALUS, CHIPS, HyperK, LBNO

LSND, MiniBooNE, KARMEN, SciBooNE, Bugey, Goesgen, Planck, MicroBooNE, IsoDAR, NuSTORM, LAr1, SOX

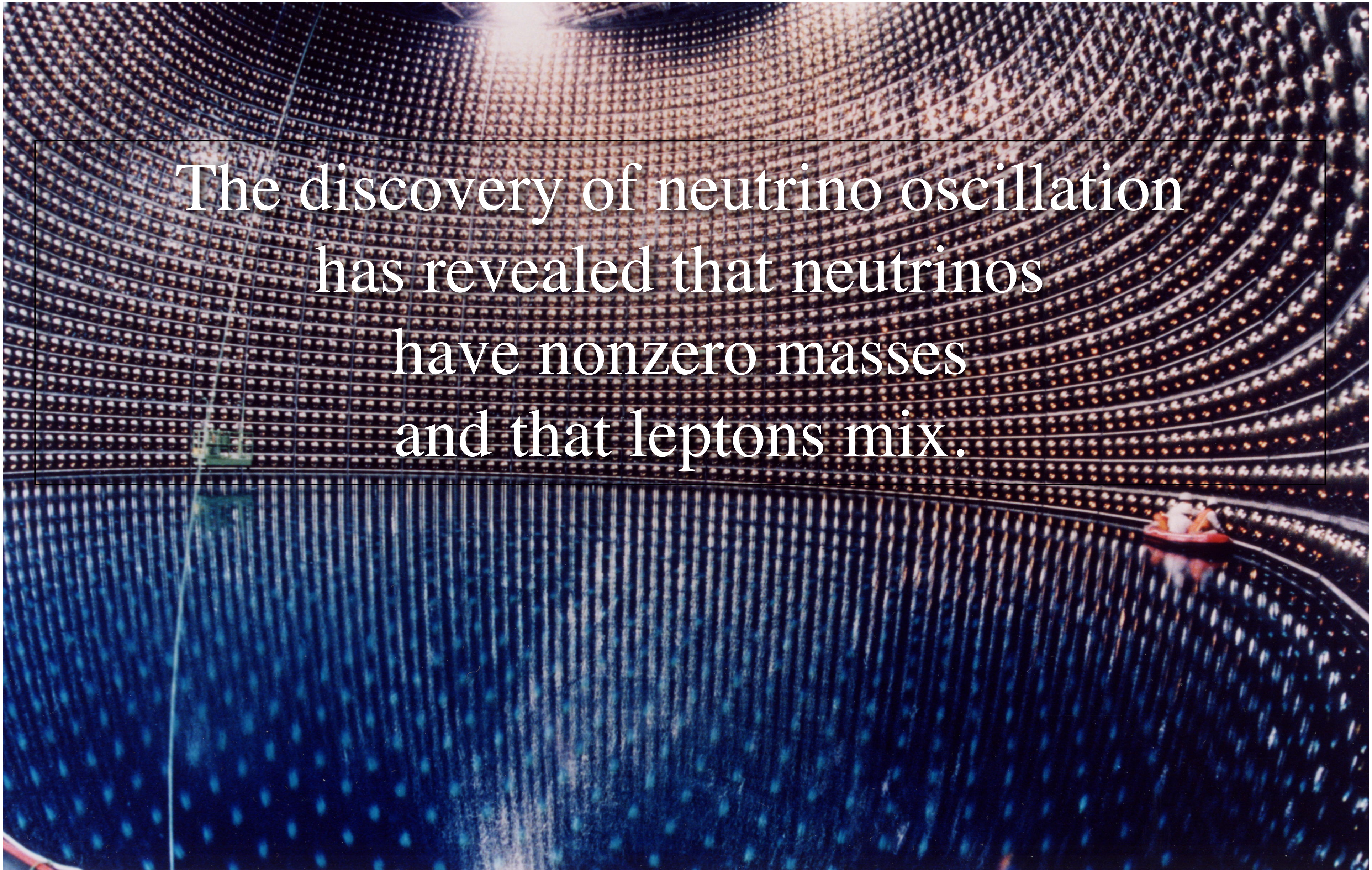
CHOOZ, Palo Verde, KamLAND, Daya Bay, RENO, DCHOOZ

Heidelberg-Moscow, CUORE, EXO, Majorana, GERDA, SNO+, KamLAND-ZEN

Mainz, Troitsk, KATRIN, Project 8

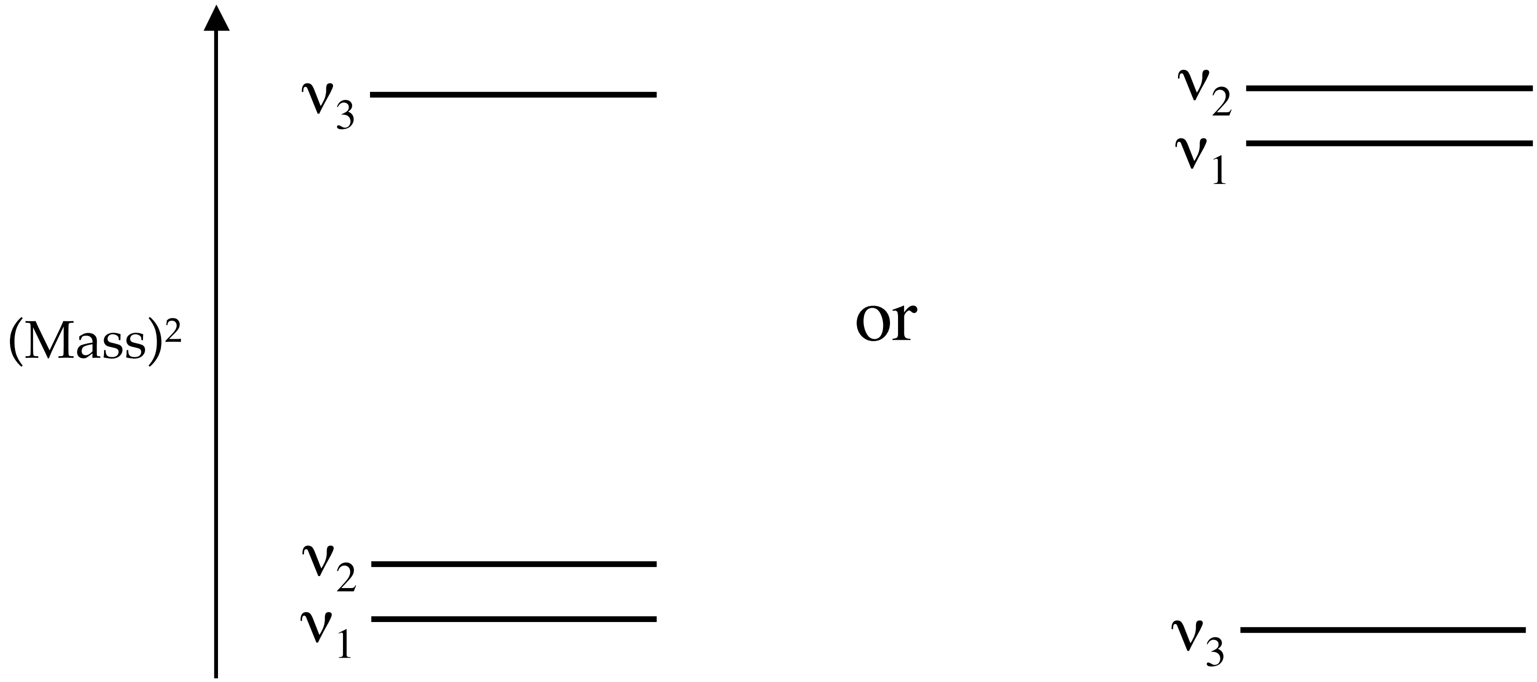
IceCube, ANTARES

The discovery of neutrino oscillation
has revealed that neutrinos
have nonzero masses
and that leptons mix.



What We Have Learned

The Three – Neutrino (Mass)^2 Spectrum

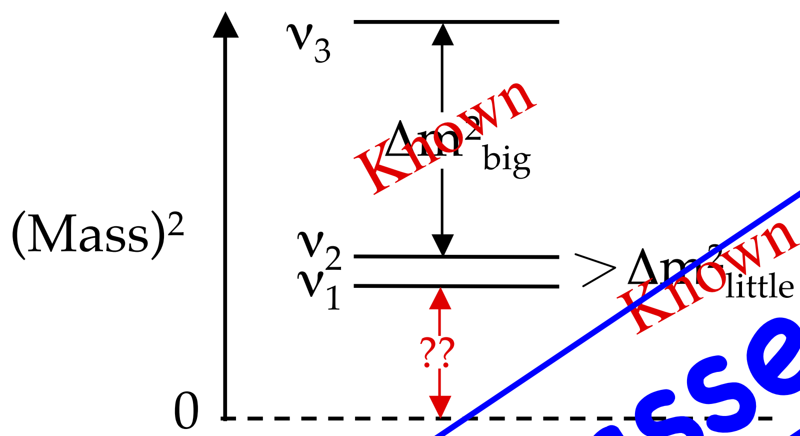


Normal   Inverted

$$\Delta m^2_{21} \equiv m^2_2 - m^2_1 \cong 7.5 \text{ x } 10^{-5} \text{ eV}^2, \qquad \Delta m^2_{32} \cong 2.4 \text{ x } 10^{-3} \text{ eV}^2$$

There might be more mass eigenstates.

Constraints On the Absolute Scale of Neutrino Mass



How far above zero is the whole pattern?

Neutrino masses are tiny

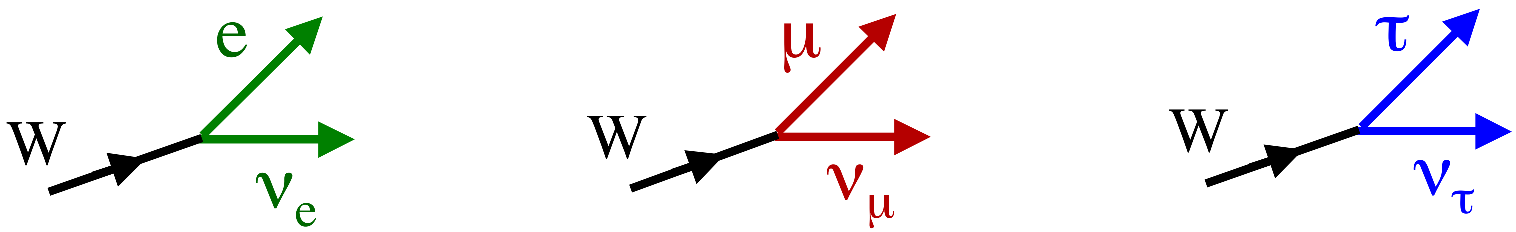
Cosmology, under certain assumptions ➡ $\sum m(\nu_i) < 0.23$ eV

All i

Tritium beta decay ➡ $\langle m_\beta \rangle \equiv \sqrt{\sum_i |U_{ei}|^2 m(\nu_i)^2} < 2$ eV

$$\text{Mass}[\text{Heaviest } \nu_i] > \sqrt{\Delta m^2_{\text{big}}} > 0.04 \text{ eV}$$

ν_e, ν_μ, ν_τ Are Not the Mass Eigenstates



ν_e, ν_μ, and ν_τ are ***superpositions*** of the mass eigenstates:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\, |\nu_i\rangle \quad .$$

Neutrino of flavor α = e, μ, or τ

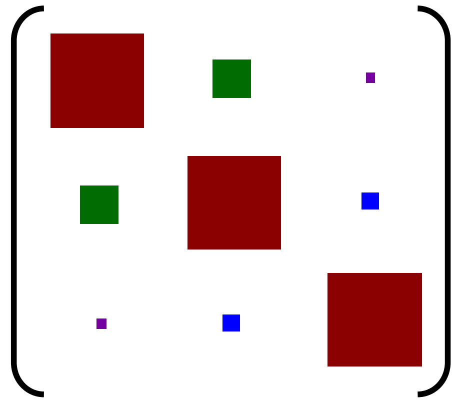
Neutrino of definite mass m_i

Unitary Leptonic Mixing Matrix

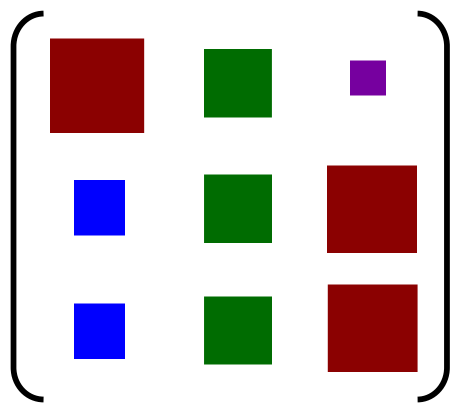
Leptonic Mixing

The Quark and Lepton Mixing Matrices

Quark mixing matrix =



Lepton mixing matrix =



In terms of the ***sizes*** of their elements, the two matrices look very different:

The Lepton Mixing Matrix U

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij}$$
$$s_{ij} \equiv \sin\theta_{ij}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Note big mixing!

$\underbrace{\theta_{12} \approx 33°,\ \theta_{23} \approx 36\text{-}42° \ \underline{\text{or}}\ 48\text{-}54°,}$ $\theta_{13} \approx 8\text{-}9°$ ***No more worry!***

The phases violate CP. δ would lead to $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$.

But note the crucial role of $s_{13} \equiv \sin\theta_{13}$.

However, we know nothing about the phases.

Where Do the Tiny Neutrino Masses Come From?

Perhaps, neutrino masses have the same source as the quark and charged lepton masses:

The Standard Model (SM) Higgs mechanism for fermion masses.

Coupling constant

Must add to the SM

$$\mathcal{L}_{SM} = y\overline{H}^0\overline{\nu}_L\nu_R \Rightarrow y\underbrace{\left\langle \overline{H}^0 \right\rangle_0}_{\text{Vacuum expectation value}}\overline{\nu}_L\nu_R \equiv m_\nu\overline{\nu}_L\nu_R$$

SM Higgs field

$$\left\langle \overline{H}^0 \right\rangle_0 \equiv v = 174\ \text{GeV}\ , \ \text{so} \quad y = \frac{m_\nu}{v} \sim \frac{0.1\,\text{eV}}{174\ \text{GeV}} \sim 10^{-12}$$

A coupling constant this much smaller than unity leaves many theorists skeptical.

— An alternative possibility —

Majorana masses and the **See-Saw** picture

The See-Saw model is the most popular theory of why neutrinos are so light.

The straightforward (type-I) See-Saw model adds to the SM 3 heavy neutrinos N_i, with —

Large Majorana masses

SM lepton doublet

$$\mathcal{L}_{\text{new}} = -\frac{1}{2}\sum_i m_{N_i} N_{iR}^2 \quad + \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} y_{\alpha i}\left[\overline{\nu}_{\alpha L}\overline{H^0} - \overline{\ell}_{\alpha L}H^-\right]N_{iR} + h.c.$$

SM Higgs doublet

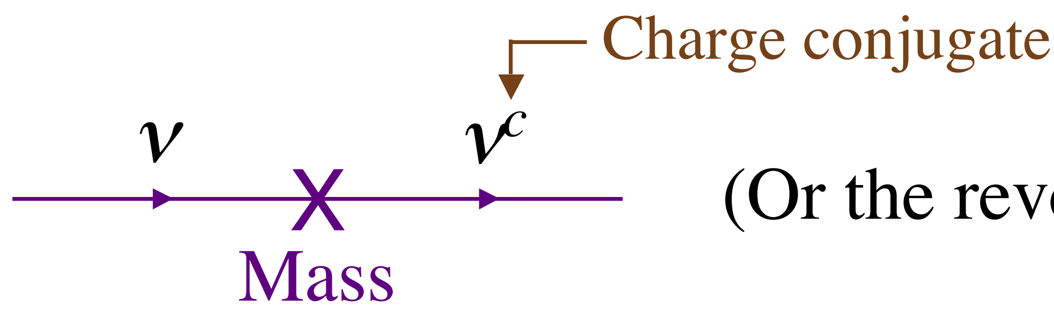
Yukawa coupling matrix

In this picture, there is still a coupling of the neutrinos to the SM Higgs field.

In addition, there is a new ingredient:
large Majorana masses,
whose origin is unknown physics.

Majorana masses cannot come from the standard, linear Yukawa coupling of neutrinos to the SM Higgs field.

Majorana mass terms have the effect —



(Or the reverse)

Because they mix neutrino and antineutrino,
they do not conserve $L \equiv$ #(Leptons) – #(Antileptons).

There is then no conserved quantum number
to distinguish antineutrinos from neutrinos.

The neutrino mass eigenstates ν_i are of the form $\nu + \nu^c$,
so that clearly $\overline{\nu_i} = \nu_i$.

Why Majorana Masses $\Longrightarrow$ $\overline{\nu_i} = \nu_i$

As a result of $K^0 \longleftrightarrow \overline{K^0}$ mixing, the neutral K mass eigenstates are —

$$K_{S,L} \cong (K^0 \pm \overline{K^0})/\sqrt{2} \; . \qquad \overline{K_{S,L}} = K_{S,L} \; .$$

As a result of $\nu \longleftrightarrow \nu^c$ mixing, the neutrino mass eigenstate ν_i is —

$$\nu_i = \nu + \nu^c = \text{``}\, \nu + \overline{\nu} \,\text{''}. \quad \overline{\nu_i} = \nu_i \; .$$

- **Presence of Majorana masses**
- **Non-conservation of *L***
- **Self-conjugacy of neutrinos ($\bar{\nu} = \nu$)**

— are all signature predictions of the See-Saw picture.

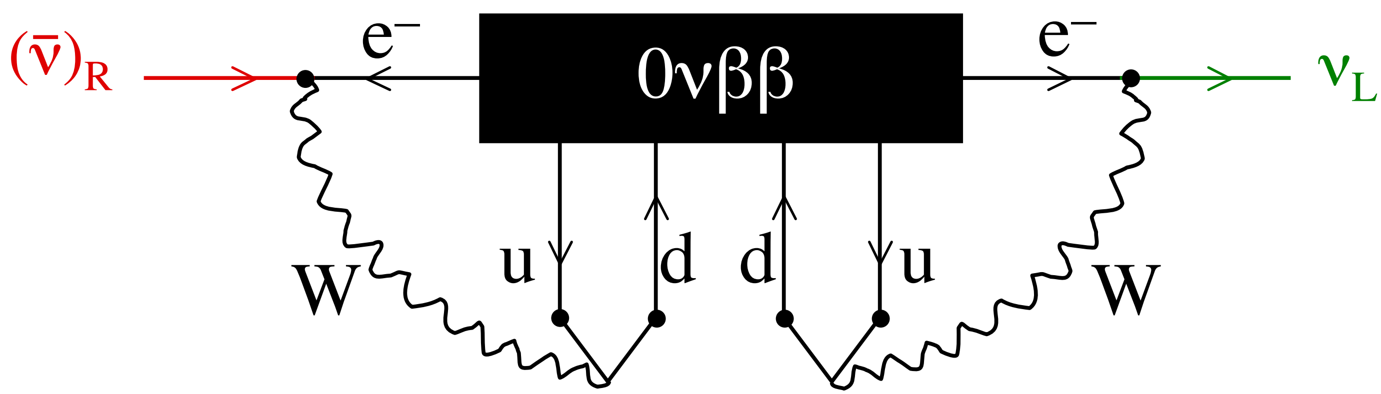
All three predictions would be confirmed by the observation of neutrinoless double beta decay (0νββ)

$\Delta L = 2$

does not conserve L.

Whatever diagrams cause $0\nu\beta\beta$, its observation would imply the existence of a Majorana mass term:

(Schechter and Valle)



$(\bar{\nu})_R \rightarrow \nu_L$: A (tiny) Majorana mass term

$\therefore\ 0\nu\beta\beta \Rightarrow \bar{\nu}_i = \nu_i$

One consequence of the See-Saw picture is —

The See-Saw Relation

Leptonic mixing matrix

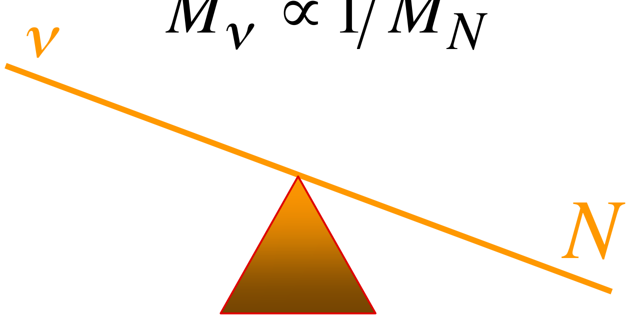
Heavy N mass eigenvalues

$$U M_\nu U^T = -v^2 \left(y \, M_N^{-1} y^T \right)$$

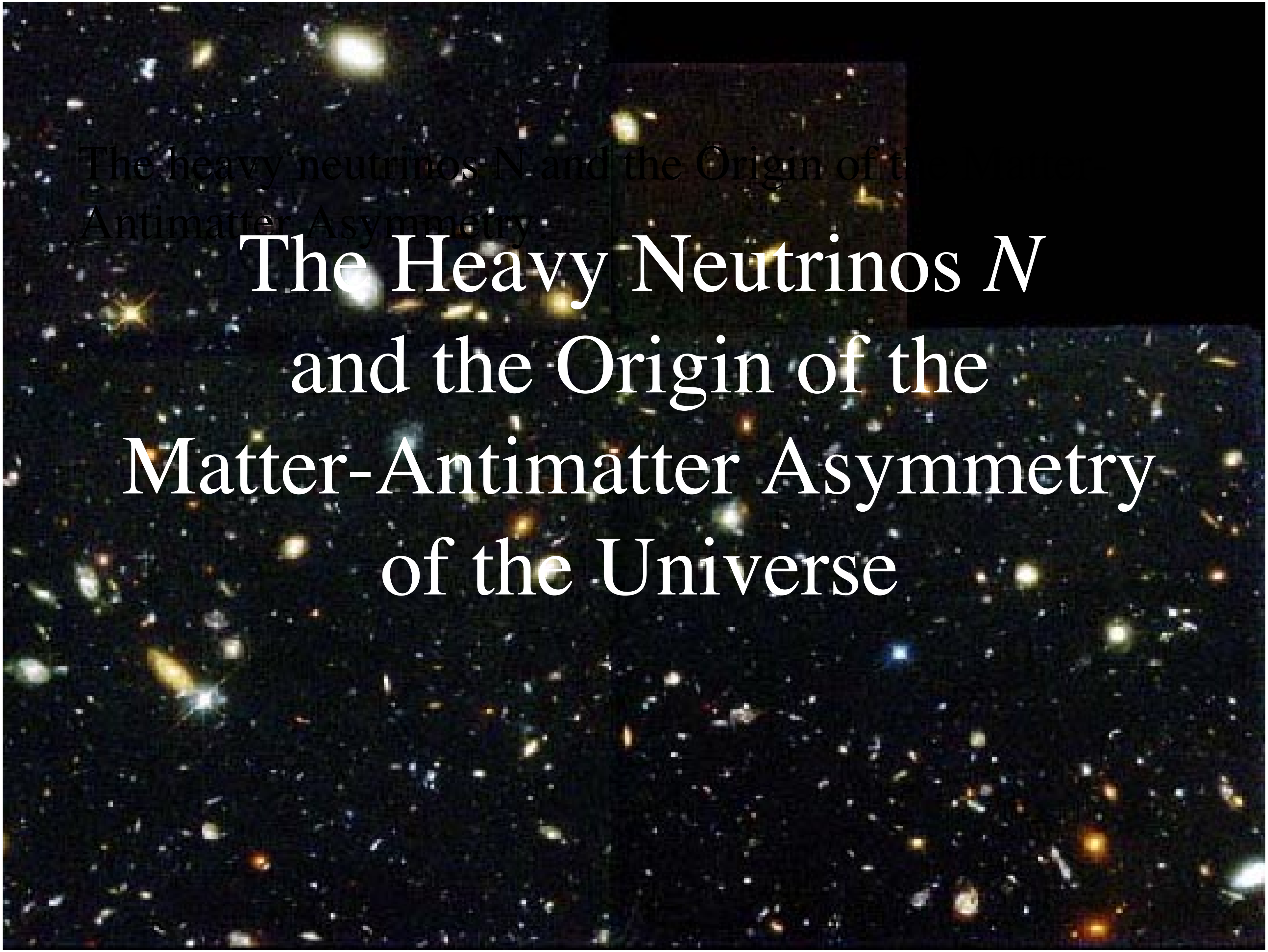
Light ν mass eigenvalues

The Higgs vev, 174 GeV

$$M_\nu \propto 1/M_N$$



Yanagida; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic; Minkowski


The heavy neutrinos N and the Origin of t[redacted]
Antimatter Asymmetry
The Heavy Neutrinos *N*
and the Origin of the
Matter-Antimatter Asymmetry
of the Universe

The Cosmic Puzzle

Today: $B \equiv \#(\text{Baryons}) - \#(\text{Antibaryons}) \neq 0.$

Standard cosmology: Right after the Big Bang, $B = 0.$

Also, $L \equiv \#(\text{Leptons}) - \#(\text{Antileptons}) = 0.$

How did $B = 0 \Rightarrow B \neq 0$?

Sakharov: $B = 0 \Rightarrow B \neq 0$ requires $\cancel{CP}$.

The $\not{CP}$ in the quark mixing matrix, seen in B and K decays, leads to much too small a $B - \overline{B}$ asymmetry.

If ***quark*** $\not{CP}$ cannot generate the observed $B - \overline{B}$ asymmetry, can some scenario involving ***leptons*** do it?

The candidate scenario: ***Leptogenesis***, a very natural consequence of the See-Saw picture.

(Fukugita, Yanagida)

During the ***hot*** Big Bang, the N_i were made.

~~CP~~ phases in the matrix y would have led to —

$$\Gamma\left(N \rightarrow \ell^- + H^+\right) \neq \Gamma\left(N \rightarrow \ell^+ + H^-\right)$$

and

CP mirror image modes

$$\Gamma\left(N \rightarrow \nu + H^0\right) \neq \Gamma\left(N \rightarrow \overline{\nu} + \overline{H^0}\right)$$

In the See-Saw, $\overline{N} = N$

This violates CP in the leptonic sector, and violates lepton number L.

Starting with a universe with $L = 0$, these decays would have produced one with $L \neq 0$.

Next —

The Standard-Model ***Sphaleron*** process,
which does not conserve Baryon Number B,
or Lepton Number L, but does conserve $B - L$, acts.

$$B_i = 0 \qquad L_i \neq 0$$

$$\longrightarrow \quad \text{Sphaleron Process} \quad \longrightarrow$$

$$B_f \cong -\frac{1}{3} L_i \qquad L_f \cong \frac{2}{3} L_i \cong -2B_f$$

Initial state from N decays

Final state

There is now a nonzero Baryon Number B.

There are baryons, but ~ no antibaryons.

Reasonable couplings y give the observed value of B.

What *N* masses are required?

$$U M_\nu U^T = -v^2 \left(y\, M_N^{-1} y^T \right) \quad \Rightarrow \quad M_\nu \sim \frac{v^2 y^2}{M_N}$$

The light neutrino masses $M_\nu \sim 0.1$ eV.

$v = 174$ GeV.

y^2 is constrained by the observed Baryon Number.

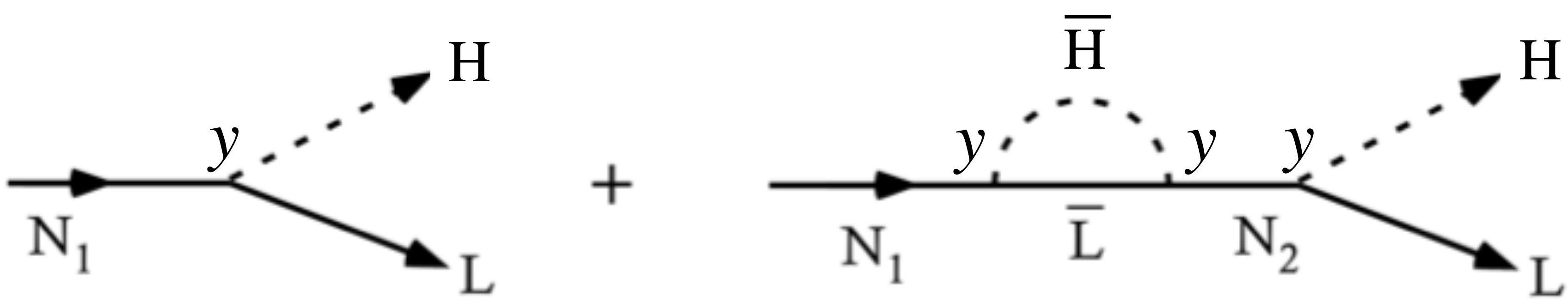
The CP-violating asymmetry between the N decay rates,

ν or ℓ^- H^0 or H^+

$$\varepsilon_{CP} \equiv \frac{\Gamma(N \to LH) - \Gamma(N \to \overline{L}\overline{H})}{\Gamma(N \to LH) + \Gamma(N \to \overline{L}\overline{H})} \quad ,$$

which produces a nonzero Lepton Number,

arises from interference between diagrams such as —



Note ε_{CP} is $\propto (y^4/y^2) = y^2$.

Getting the observed Baryon Number requires $y^2 \sim 10^{-5}$.

Then the see-saw relation —

$$M_\nu \sim \frac{v^2 y^2}{M_N}$$

$$\Rightarrow \quad M_N \sim 10^{(9-10)}\ \mathrm{GeV}.$$

This places the heavy neutrinos N far out of reach of the LHC.

$\Rightarrow$ ***The possibility of Leptogenesis must be explored at the Intensity Frontier.***

Number of leptonic parameters in the See-Saw picture: 21

Number of these parameters that can be measured without producing the heavy neutrinos N: 12

Since 21 > 12, laboratory measurements today cannot pin down what happened in the early universe.

Can there be $\cancel{CP}$ in ν oscillation but no leptogenesis? Yes.

Can there be leptogenesis but no $\cancel{CP}$ in ν oscillation? Yes.

Is either of these possibilities likely? ***NO!***

An Argument

(BK, arXiv:1012.4469)

The See-Saw Relation

$$\underbrace{U}_{\text{Leptonic mixing matrix}} \underbrace{M_\nu}_{\text{Light } \nu \text{ mass eigenvalues}} U^T = -\underbrace{v}_{\text{The Higgs vev, a real number}}{}^2 \left(y \underbrace{M_N^{-1}}_{\text{Heavy } N \text{ mass eigenvalues}} y^T \right)$$

$$\left(\underbrace{U M_\nu U^T}_{\text{Outputs}} = -v^2 \underbrace{\left(y\, M_N^{-1} y^T \right)}_{\text{Inputs, in } \mathcal{L}} \right)$$

Through ***U***, the phases in ***y*** lead to $\cancel{CP}$ in light neutrino oscillation.

$$P(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta) =$$

Distance

e, μ, or τ

$$= \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

$$\underset{(-)}{+}2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(\Delta m^2_{ij}\frac{L}{2E})$$

Neutrino $(\text{Mass})^2$ splitting

Energy

Generically, leptogenesis and light-neutrino $\cancel{CP}$ imply each other.

A Special Situation

If all N_i masses > 10^{12} GeV, the lepton number L produced by the N_i decays depends only on $\mathrm{Im}(y^\dagger y)$.

y can be written as $y = \frac{1}{iv} U M_\nu^{1/2} R M_N^{1/2}$, where R is an unknown complex matrix satisfying $RR^T = 1$.

(Casas, Ibarra)

Thus $y^\dagger y = \frac{1}{v^2} M_N^{1/2} R^\dagger M_\nu R M_N^{1/2}$, which does not involve U.

In this situation, the phases that drive leptogenesis are independent of those in U.

However —

By placing an upper bound on the reheating temperature of the universe, supersymmetry suggests that the lightest N_i must have mass $\sim 10^9$ GeV.

(Kohri, Moroi, Yotsuyanagi)

Then $\cancel{CP}$ phases in U, which produce $\cancel{CP}$ in ν oscillation, and influence the rate for neutrinoless double beta decay, lead also to a baryon-antibaryon asymmetry.

(Abada, Davidson, Ibarra, Josse-Michaux, Losada, Nardi, Nir, Racker, Riotto, Roulet; Pascoli, Petcov, Riotto, Rodejohann)

The Leptogenesis — Neutrino ~~CP~~ Connection In Modified See-Saws

Are leptogenesis and light-neutrino ~~CP~~ still connected in modified, non-type-I, See-Saw models?

A small sampling of modified See-Saws has been carried out.

(BK, Petcov, Qin, Zhang, Chen)

The Conclusion: In general, leptogenesis and light-neutrino ~~CP~~ are connected, because the ~~CP~~ that drives leptogenesis and the one observable in light-neutrino behavior have a common source.

In this small sampling, we found one exception:

A See-Saw model so constructed that the heavy neutrinos *N* would be light enough, and interact with quarks strongly enough, to be observable at the LHC.

(BK, Segre)

This model is testable at the LHC.

But the price it pays for having an LHC-range heavy sector is to disconnect leptogenesis and light-neutrino physics.

Generically, leptogenesis and light-neutrino ~~CP~~ do imply each other.

The observation of light-neutrino ~~CP~~ would make it more plausible that the baryon asymmetry of the universe arose, at least in part, through leptogenesis.

The Heart of Leptogenesis

During the ***hot*** Big Bang, the N_i were made.

$\cancel{CP}$ phases in the matrix y would have led to —

$$\Gamma\left(N \to \ell^- + H^+\right) \neq \Gamma\left(N \to \ell^+ + H^-\right)$$

and

$$\Gamma\left(N \to \nu + H^0\right) \neq \Gamma\left(N \to \overline{\nu} + \overline{H^0}\right)$$

This violates CP in the leptonic sector, and violates lepton number L.

These are the key ingredients of Leptogenesis.

Starting with a universe with $L = 0$,
these decays would have produced one with $L \neq 0$.

To establish that there is CP violation in the leptonic sector:

Show that there is CP violation in neutrino oscillation.

To establish that there is lepton number violation:

Show that neutrinoless double beta decay occurs.

$\Delta L = 2$

does not conserve L.

Q: Don’t we expect CP violation in neutrino oscillation, so finding it won’t teach us anything?

A: Didn’t we expect the leptonic mixing angles to be small?

CP is a fundamental symmetry.

Is its nonconservation
special to quark mixing?

Or, does it occur in both
quark and lepton mixing,
as suggested by Grand Unified Theories,
which unify the quarks and the leptons?

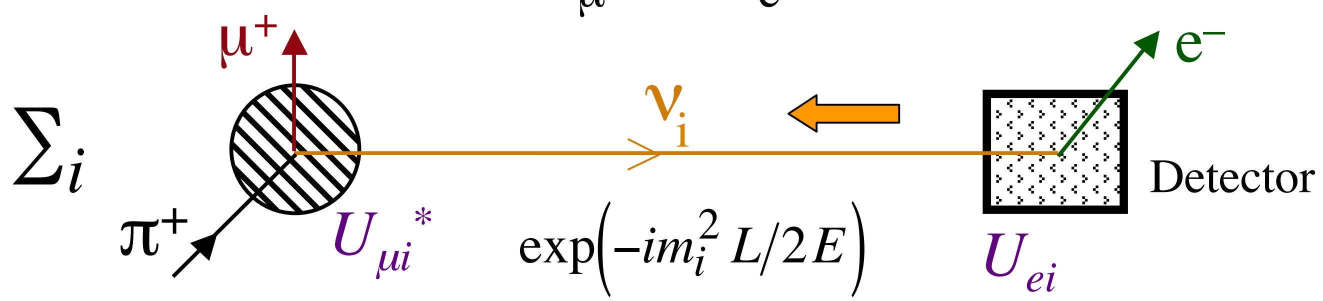
To seek ~~CP~~ in neutrino oscillation, experiments will look for the CP violation —

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \neq P(\nu_\mu \to \nu_e)$$

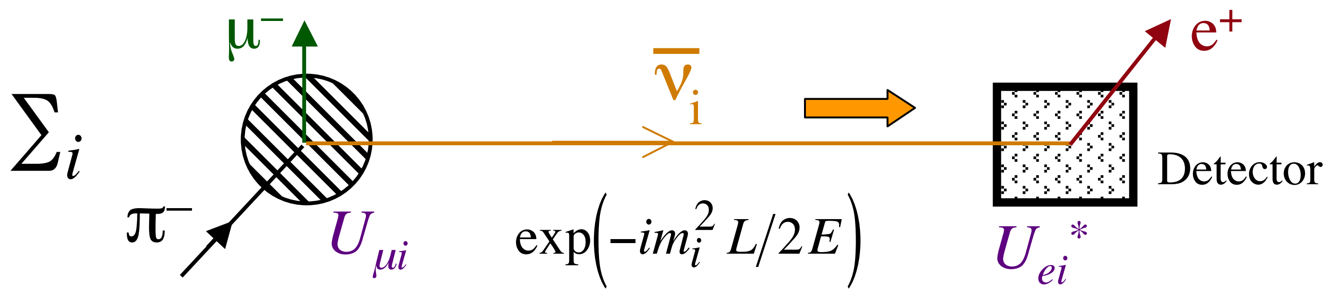
$\mathcal{Q}$: *Can CP violation still lead to $\mathcal{P}(\overline{\nu}_\mu \to \overline{\nu}_e) \neq \mathcal{P}(\nu_\mu \to \nu_e)$ when $\bar{\nu} = \nu$?*

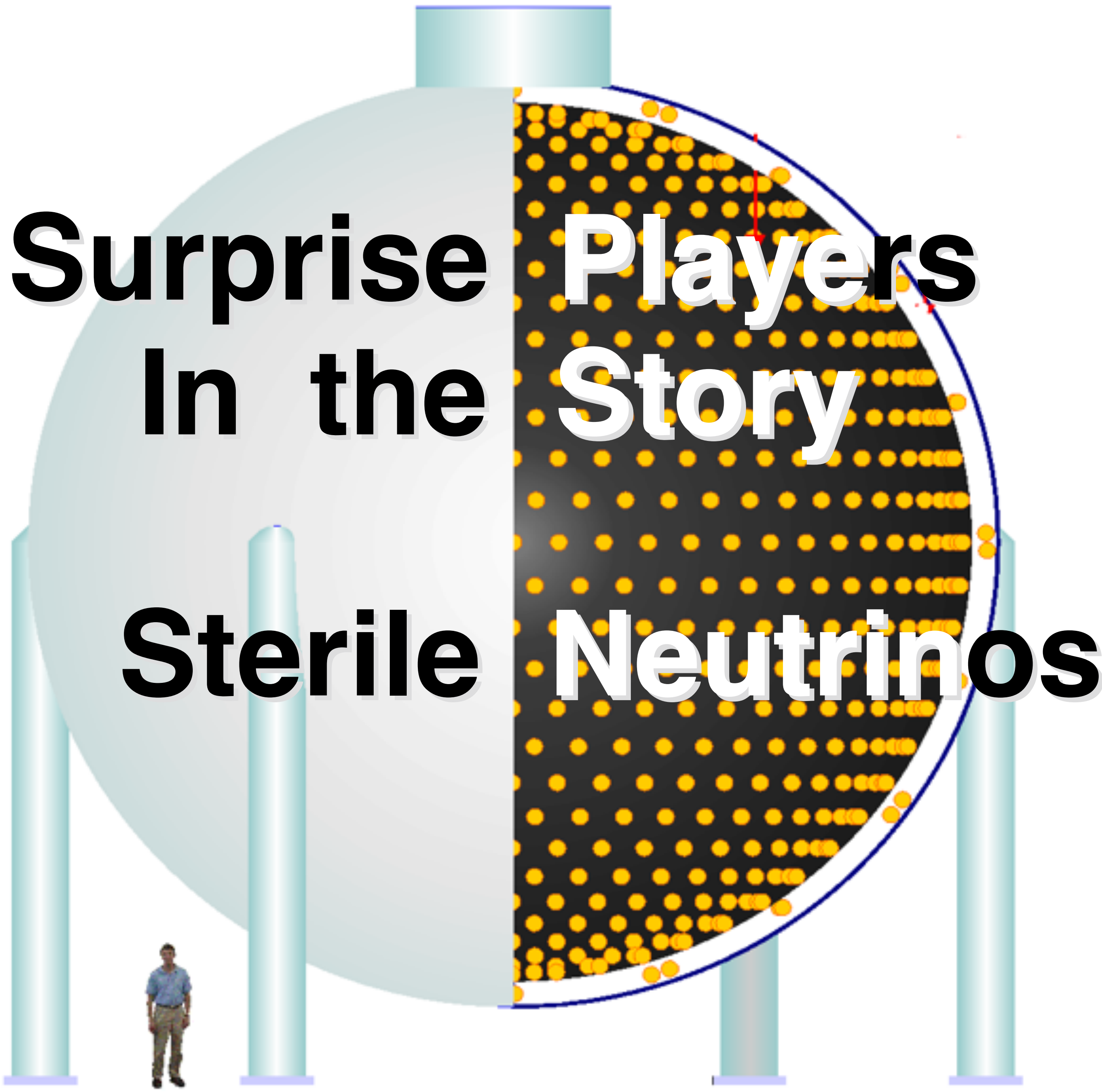
$\mathcal{A}$: *Certainly!*

Compare $\nu_\mu \to \nu_e$



with "$\overline{\nu}_\mu \to \overline{\nu}_e$"




Surprise Players
In the Story
Sterile Neutrinos

Sterile Neutrino

One that does not couple to the SM *W* or *Z* boson

A "sterile" neutrino may well couple to some non-SM particles. These particles could perhaps be found at LHC or elsewhere.

The heavy See-Saw partner neutrinos N_i interact with the rest of the world only through the Yukawa coupling —

SM lepton doublet

$$\mathcal{L}_{\text{Yukawa}} = \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} y_{\alpha i}\left[\bar{\nu}_{\alpha L}\overline{H^0} - \bar{\ell}_{\alpha L}H^-\right]N_{iR} + h.c.$$

SM Higgs doublet

Yukawa coupling matrix

The N_i do not couple to the SM W or Z boson.

∴ The N_i are sterile neutrinos.

Are there also ***light*** sterile neutrinos with masses ~ 1 eV?

Some Hints — First LSND

The LSND experiment at Los Alamos reported a ***rapid*** $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation at $L(km)/E(GeV) \sim 1$.

$$P\left(\overline{\nu_\mu} \to \overline{\nu_e}\right) = \sin^2 2\theta \, \sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right] \sim 0.26\%$$

From μ^+ decay at rest; E ~ 30 MeV

~ 1eV^2 in contrast to $\Delta m^2_{32} = 2.4 \times 10^{-3}\ \mathrm{eV}^2$, $\Delta m^2_{21} = 7.5 \times 10^{-5}\ \mathrm{eV}^2$

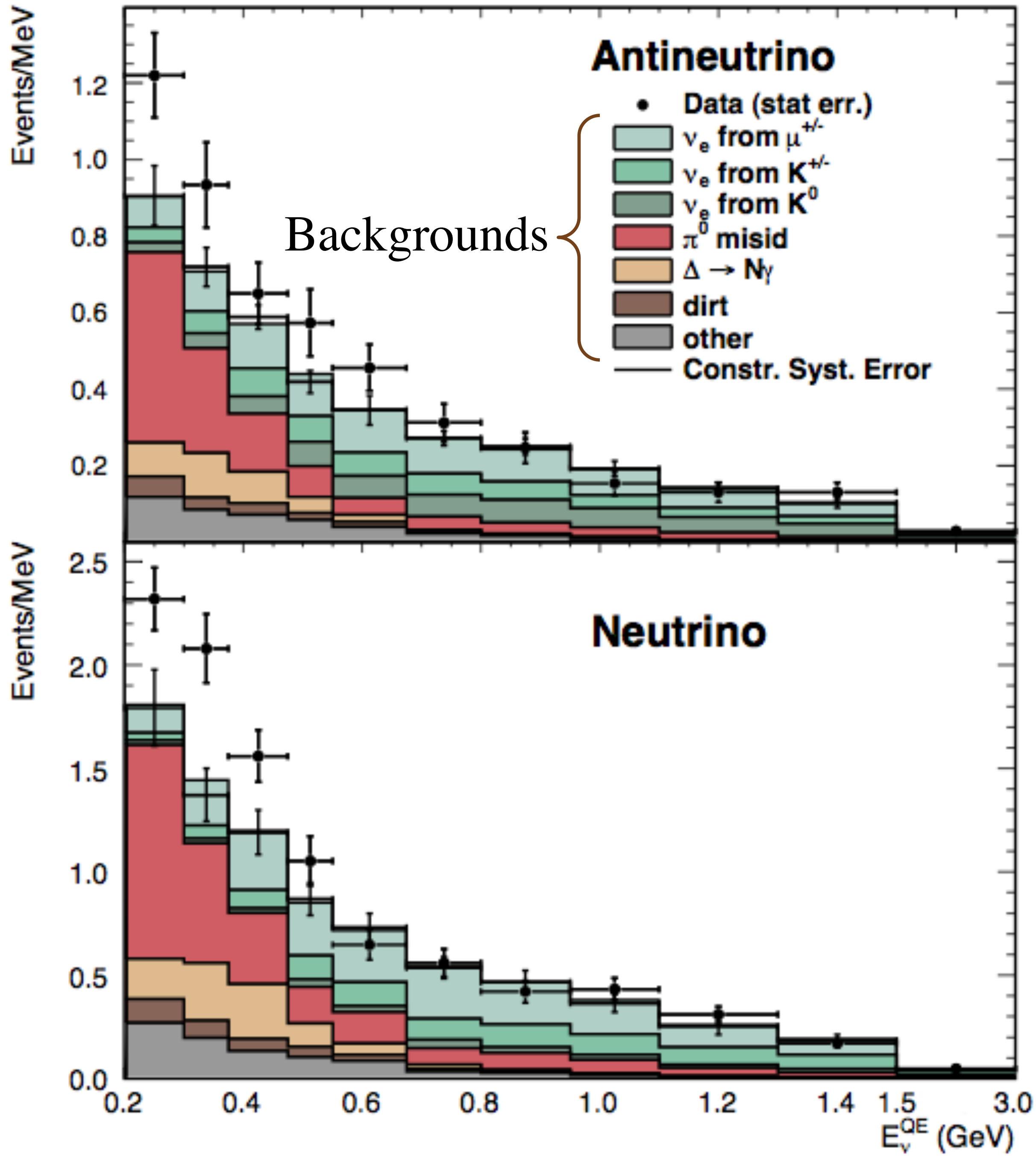
At least **4** mass eigenstates

{from measured $\Gamma(Z \to \nu\bar{\nu})$} At least **1** sterile neutrino

The Hint From MiniBooNE

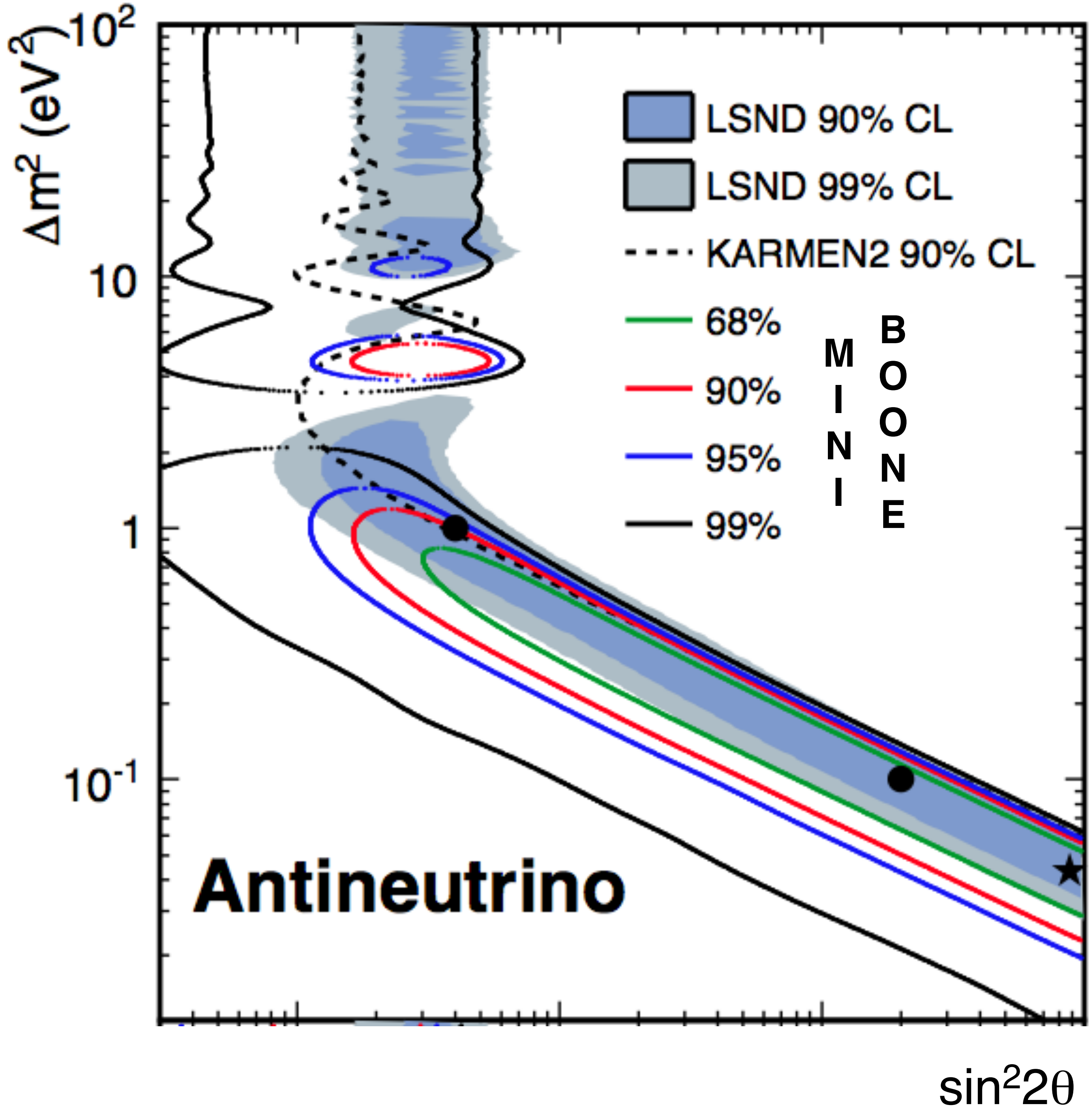
In MiniBooNE, both L and E are ~ 17 times larger than they were in LSND, and L/E is comparable.

MiniBooNE has reported both $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ results.



MiniBooNE
1303.2588

78.4 ± 28.5 excess $\bar{\nu}$ events, and 162.0 ± 47.8 excess ν events



MiniBooNE and LSND allowed regions overlap.

Two-level mass spectrum assumed.

From 1303.2588

A Hint From Reactors

The measured $\bar{\nu}_e$ flux at (10 – 100)m from reactor cores is ~ 6% below the theoretically expected value.

(Mueller et al., Mention et al., Huber)

Are the $\bar{\nu}_e$ disappearing by oscillating into another flavor?

The $\bar{\nu}_e$ energy is ~ 3 MeV, so at, say, 15m,

$$L(\text{m})/E(\text{MeV}) = L(\text{km})/E(\text{GeV}) \sim 5.$$

If the $\bar{\nu}_e$ are oscillating away,

$$\sin^2\left[1.27\,\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right] \sim 1 \Longrightarrow \Delta m^2\left(eV^2\right) \sim 1\,.$$

The Hint From ^{51}Cr and ^{37}Ar Sources

These radioactive sources were used
to test gallium solar ν_e detectors.

$$\frac{\text{Measured event rate}}{\text{Expected event rate}} = 0.86 \pm 0.05$$

(Giunti, Laveder)

Rapid disappearance of ν_e flux
due to oscillation with a large Δm^2??

The Constraint (?) From Cosmology

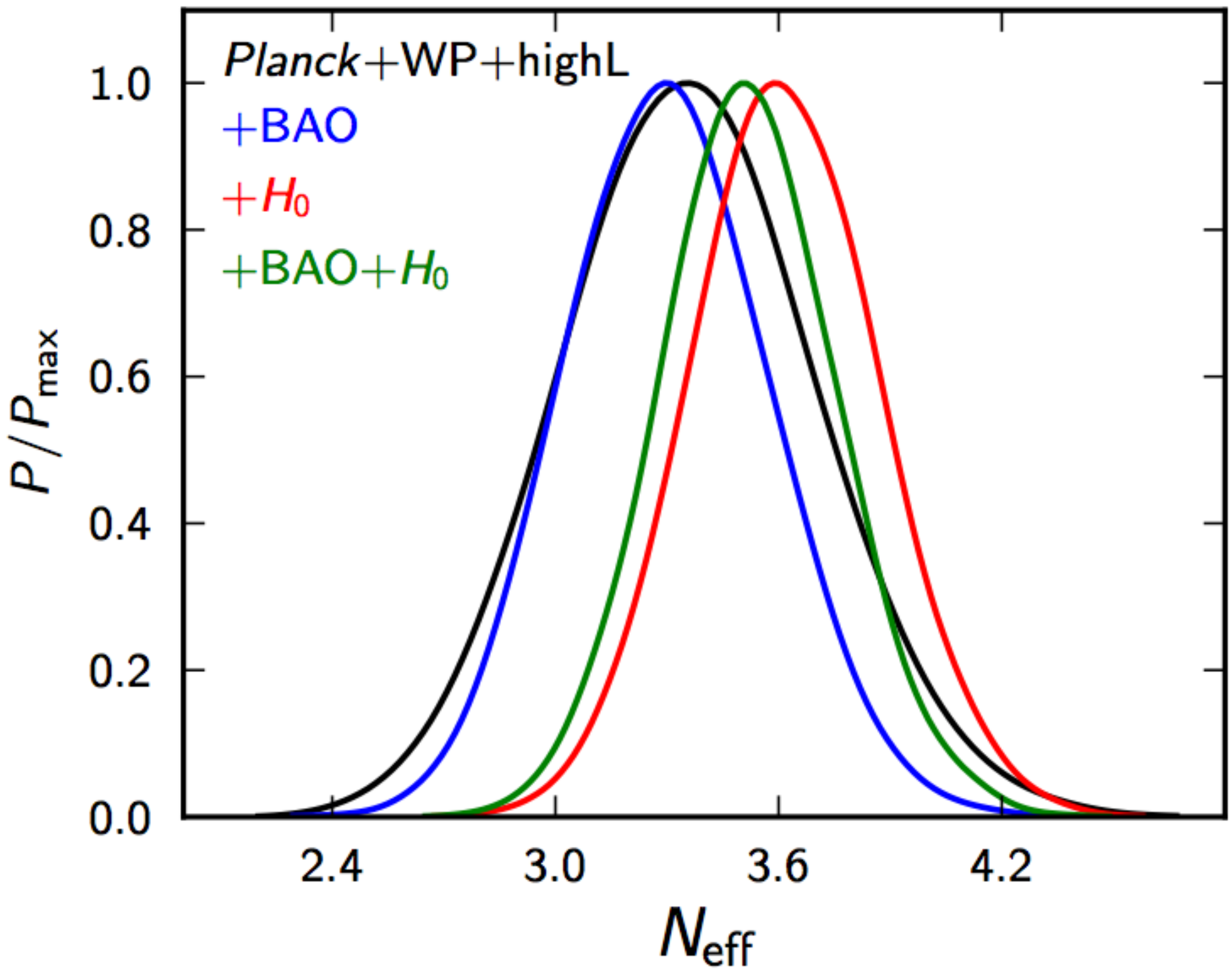
Big Bang Nucleosysthesis (BBN) and CMB
anisotropies count the effective number
of relativistic degrees of freedom, N_{eff}, at early times.

Light sterile neutrinos mixed with the active ones
as required by the terrestrial anomalies
would very likely have thermalized in the early universe.

Then N_{eff} grows by 1 for each sterile species.

There is recent evidence from ***Planck*** CMB data on N_{eff} .

The favored N_{eff} depends on whether one takes into account a competing value of the Hubble constant H_0.



So, is $N_{eff} = 3$, or more than 3?

$\sum_i m(\nu_i)$ In the Early Universe

Large Scale Structure in the universe and the CMB probe this sum of the neutrino masses, ***assuming*** that all ν_i have thermalized in the early universe.

$$\sum_i m(\nu_i) < 0.23 \text{ eV} \qquad \begin{pmatrix} \text{Planck + WP +} \\ \text{high L + BAO} \end{pmatrix}$$

Possible tension with terrestrial experiments if $\Delta m^2 > 1 \text{ eV}^2$.

However, in cosmology, there are parameter degeneracies.

Q**:** If light sterile neutrinos exist, how are leptogenesis, light-neutrino $\cancel{CP}$, and the connection between them affected?

A**:** If at least 2 light sterile neutrinos exist, $\cancel{CP}$ at short baselines becomes possible.

The connection between light-neutrino $\cancel{CP}$ and leptogenesis is model dependent.

Example: A conventional See-Saw, but a symmetry allows one of the 3 sterile N_i to become light. Leptogenesis and light-neutrino $\cancel{CP}$ are connected more-or-less as usual.

(Mohapatra)

Conclusion

Some very interesting questions will be addressed by the future experimental neutrino program.

Go for it!